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Mechanical and Comfort Properties of Hemp and Hemp Blend Fabrics: A Comprehensive Review

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Abstract
Hemp fabrics are well known for their mechanical strength, durability, and eco-friendliness but the inherent stiffness poses challenges for apparel applications. To develop yarns and fabrics with the desired mechanical and comfort performance, the interaction between yarn and fabric parameters and their corresponding influence plays an important part. Key findings indicate that ring-spun yarns enhance tensile strength, while rotor and vortex spinning improve abrasion resistance and smoothness. Higher twist levels increase mechanical strength but reduce moisture-wicking, whereas lower twist improves flexibility and comfort. Among fabric structures, plain weaves provide superior tensile strength, whereas twill and satin weaves enhance drape. Additionally, blending hemp with cotton, Tencel, or flax improves softness, breathability, and overall wear ability without compromising durability. Understanding these factors is essential to optimizing hemp and hemp blend textiles apparel, activewear, and functional fabric. Hence, this review aims to offer valuable insights for researchers and industry professionals working towards the development of sustainable hemp-based fabrics.

Keywords: *Hemp, hemp blend, mechanical properties, comfort performance, woven fabric.*

1. Introduction

Hemp (Cannabis sativa L.) is among the oldest known fiber crops. It is commonly used for textiles, ropes, and other industrial uses. This renewed interest in this crop, however, refers to its sustainable and biodegradable aspects, together with its remarkable mechanical properties (Manaia, 2019). As a bast fiber, hemp possesses high-tensile strength, durability, and natural antimicrobial properties, which could make it a highly promising replacement for commercial textile fibers like cotton and polyester (Zimniewska, 2022). On the other hand, hemp fibers are naturally tough and durable, but they lack flexibility, which means they can't be used in applications where comfort and softness are paramount (Kozłowski & Mackiewicz-Talarczyk, 2012). [1-5] The fashion industry significantly impacts the environment, contributing to 10% of global carbon emissions and 20% of industrial water pollution (*Ellen MacArthur Foundation, 2017*). Compared to cotton, hemp cultivation is more sustainable, requiring 50% less water, no synthetic pesticides, and yielding more fiber per hectare (*Textile Exchange, 2021*). Additionally, hemp's ability to regenerate soil through phytoremediation and its low-energy processing needs make it a strong candidate for sustainable fashion (*Shen, 2011*). Reports from the Sustainable Apparel Coalition highlight that incorporating hemp into textiles can lower resource consumption and carbon footprints, supporting a circular economy approach (*SAC, 2022*). However, despite these sustainability benefits, hemp adoption in textiles remains slow due to processing difficulties, high production costs, and its naturally coarse

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Page No: 654 - 664

texture (*Bismarck et al., 2005*). Advancements in fiber processing techniques, including enzymatic retting and innovative spinning methods, are essential to improve fiber softness, drape, and overall commercial viability (*Faruk et al., 2012*). Cotton sustainability has declined as research's revealed that the pesticide and fertiliser intensive crop not only required excessive land but also water. Although, organic cotton is claimed to be sustainability, it only account to 1% of all cotton production, and it can't be seen as a universal substitute (Tausif et al., 2018). [6-10] To improve fabric softness, flexibility, and wearability, while preserving the durability and eco-friendly advantages of hemp, these limitations have been counteracted by blending hemp with other fibers including cotton, Tencel, or synthetic fibers (Morton & Hearle, 2008). Studies have indicated that hemp-cotton and hemp-synthetic blends provide better tactile comfort, moisture-wicking action, and dimensional stability, without sacrificing too much of hemp's natural rigidity (Saville, 1999). Despite all these advantages, challenges such as fiber inconsistency, low dyeability, complicated manufacturing process, and high processing cost as compared to conventional fibers remain (Cook, 1984) Apart from this, the important factors that also affect the mechanical and comfort properties of hemp-based fabrics are fiber composition, yarn twist, weave structure, areal density, and thread count (Adanur, 2001). Therefore, it is essential to understand how these parameters affect fabric performance to optimize hemp textiles for various applications.

2. Effect of Yarn Parameters

2.1 Spinning Method

The mechanical and comfortab4le performance of hemp and hemp blended yarns rely considerably on yarn spinning technology, with consideration for hemp fibers' high tenacity, stiffness, and low elongation (Abo Elnaga, 2022; Özşahin et al., 2022; Rusli, 2023). Before discussing any spinning method or its impact, it is important to mention the wet spinning process of hemp, which produces hemp yarns by first immersing the hemp stalks in heated water tanks before spinning, this process softens pectins binding the fibers allowing for better separation, alignment, and drawing during yarn formation (Riddlestone, 1998; Promhuad et al., 2022; Gedik & Avinc, 2022; Tripa et al., 2023). All have agreed that ring spinning forms yarns with the greatest tenacity and elongation, with its high level of orientation of fibers and increased use of twist, with a positive contribution to the cohesion and integrity of yarns (Rusli, 2023; Özşahin et al., 2022). On the other hand, rotor spinning forms yarns with less tenacity but with increased abrasion resistance. They have an open-end orientation of fibers with increased entanglement but less cohesion (low fiber-to-fiber friction) between fibers (Abo Elnaga, 2022). Air vortex spun hemp/tencel (30/70) yarn exhibits reduced and shorter hairiness compared to ring and siro-spun yarns due to the vortex nozzle's whirling air, which removes loose fibers and minimizes protruding ends, while the turbulence-induced looping of stiff, coarse hemp fibers enhances fabric bulk, stretch, and elasticity. (Kim & Kim, 2018; Zimniewska, 2022). Besides, with its positive contribution to yarn uniformity and tenacity, compact spinning forms increased pilling, and most prominently in hemp dominant blends, with increased compaction of fibers (Puttaswamy, 2024). Compact-spun yarns yield higher tensile strength (364 N warp, 286 N weft for suiting), smoother surface, and lower pilling (4/5 rating) than ring-spun yarns due to reduced hairiness and better fiber alignment. The coarse, stiff nature of hemp fibers (dtex 2.5–3.8 vs. cotton 1.1–2.3) increases fiber slippage in ring spinning, reducing strength and surface uniformity. (Ahirwar & Behera, 2021). A critical function in hemp integration is that of ensuring that the blended yarn has both spinnability and compatibility between the fibers which ultimately leads to forming a uniform blend. Ring-spun hemp blend yarns had the highest strength due to better fiber cohesion despite hemp's rigidity. Core-spun hemp-viscose yarns (with Lycra or T400 core) improved elongation as viscose compensated for hemp's low flexibility. Dual-core hemp blend yarns (with Lycra + T400) showed reduced strength and increased imperfections, as the reduced sheath fiber proportion led to lower cohesion and uneven fiber wrapping. (Okyay et al., 2023). Elasticity and

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Page No: 654 - 664

drapeability in hemp and viscose blended yarns have a synergistic effect, overcoming hemp stiffness (Stankovic, 2024). Nevertheless, increased hemp proportion in blends brings about defects and roughness, and softening of fibers or enzymatic processing must be utilized to promote processing and comfort (Novaković et al., 2020). Besides, hemp yarns through air-jet spinning maximize thermal regulation, positioning them for summertime and sportswear fabrics (Zimniewska, 2022). In terms of durability and strength, hemp ring spinning is the preferred method. The air vortex spinning technique can further improve the yarn's tactile comfort. Although hemp is eco-friendly, its integration into high-performance fabrics is difficult. Optimal spinning performance requires precise blending to ensure the effective use of fabric.[11-19]

2.2 Yarn Count

Hemp and hemp-blend cloth performance is governed to a large degree by yarn count. Unlike cotton, where finer yarns improve strength, in hemp-blend fabrics, coarser yarns (16Ne) exhibit higher tensile and tear strength due to hemp's stiffness, high friction coefficient, and limited fiber alignment in finer counts (30Ne) (Ahirwar and Behera, 2022). Wet spinning produces finer yarn, due to easy separation and drawing operations of the fiber (Promhuad etal., 2022; Idler et al., 2011; Tripa et al., 2022). Similarly, a study on folded hemp yarns, found that folded hemp yarns enhanced tensile properties, air permeability, and compression behaviour by altering fiber orientation and reducing packing density, thereby improving comfort without compromising thermal resistance (Stankovic & Bizjak, 2014). Contrarily, coarser yarns with bigger bundle structures have higher bending stiffness, reducing drape but increasing mechanical resistance, as in woven hemp denim (Okur, 2022). Finer hemp yarns create denser structures in cloth, and such structures possess higher abrasion resistance and lower pilling, on the other hand, coarser hemp fiber has a highly porous structure, making it suitable for summer clothing with increased moisture vapor transmission and airflow (Saricam, 2022; Atav et al., 2024). In contrast, such differentiation is conspicuous in denim, with stiff, breathable fabrics produced with coarser yarns, and with a compacter, heat-conductive cloth produced with a finer yarn (Okur, 2022). Besides, high lignin in coarser hemp yarns promotes increased UV resistance (Promhuad etal., 2022; Zhang etal., 2018) and stiffness, and such a cloth is therefore resistant to wear under environmental loads (Vasile et al., 2024). Hemp yarns with a finer count have reduced air permeability with closely packed fibers, providing thermal insulation and suitability for use in winter clothes (Novaković et al., 2020). [20-25] In hemp-Tencel blends, yarns with a high yarn count make them flexible and impart a soft, silky sensation through a mix of increased orientation of fibers and reduced yarn hairiness (Kim & Kim, 2018). Yarns with a high yarn count make them less flexible and rough but mechanically stressed and elongated resistant, and such yarns can best be utilized in high-durability items such as workwear and upholstery (Öner & Kaya, 2023). All these observations make yarn fineness important in balancing durability, comfort, and thermal performance in hemp fabrics, and therefore, yarn count selection must be determined carefully for specific use.

2.3 Yarn Twit & Yarn Plying

The mechanical strength, durability, and comfort properties of hemp and hemp-blend fabrics are influenced by yarn twist to some extent. Additionally, the inherent structural characteristics of hemp fibers further influence these properties. Increased twist per inch (TPI) increases tensile and abrasion resistances, with higher twists creating higher cohesion and interlocking between and between fibers, respectively, and reducing slipping between fibers under tension (Özşahin et al., 2022). In hemp fibers, specifically, such an effect is pronounced, with higher stiffness (Young's modulus ~25 GPa) and lower elongation in comparison to cotton. Hemp fiber possesses a lumen and a channel with a capillary, and thus it is capable of moisture-wicking naturally. With higher yarn twist, such channels collapse, moisture regain decreases up to 30%, and air permeability decreases (Kim & Kim, 2018). Composite fabrics with high-twist hemp yarns exhibited lower air permeability, with yarns being packed closely and thus restricting airflow, and, in turn, the thermal comfort of fabrics decreased (Cristina, 2024). On the

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Volume: 03
Issue:03 March 2025
Page No: 654 - 664

contrary, low-twist hemp yarns (<600 TPM) have increased softness, comfort, and breathability, and can therefore be utilized in comfort and lightweight applications. It was observed that peroxide used during bleaching caused an increase in twist in hemp yarns by closing in the interstices causing an increase in twist, hence higher twist compacts the fibers, reducing the spaces that allow air and moisture to pass through, making the fabric stiffer and stronger but less breathable (Tripa et al., 2023). The effect of yarn plying (or folding) on the comfort properties has been studied and was reported that the inconsistencies along the length of yarns has reduced, with improved packing density and improved surface roughness. This ultimately lead to the increase in thermal resistance, as the increase in packing desnity lead to increase in air spaces within the yarn (Stankovic & Bizjak, 2014;; Tripa et al., 2023). Non-homogeneous yarns with low twist showed increased elongation but poor structural integrity and therefore reduced durability under sustained loading. Because hemp yarns are coarser and less flexible compared to cotton, a minimum level of twist must be present for a yarn to maintain its structure. Hence, a delicate balancing act must occur between twists to maximize durability and comfort, respectively, in terms of intended use in a finished fabric (Milosavljević and Tadić, 2005). Although there is no huge impact of yarn twist on mechanical and comforts properties, the plying of yarns does seem to produce a significant impact.

2.4 Composition (Blend)

The research in hemp and hemp blend yarn composition attests that the mechanical and comfort performance of fabrics relies to a high extent on weaving structure, processing technology, and the proportion of fiber blend. As studies reveal, a high proportion of hemp fortifies tenacity and durability with hemp's high cellulose content (70-75%) and stiff shape of fibers (Zimniewska, 2022). On the other hand, it reduces elongation and increases stiffness, and 100% hemp fabrics become less flexible compared to linen and cotton blends (Milosavljević & Tadić, 2005). Hemp/cotton and hemp/Tencel blends have been found to promote airflow and moisture wicking, with hemp's hollow shape of fibers and high moisture regain (8-12%) allowing for enhanced thermoregulation (Kim & Kim, 2018) Furthermore, the inherent anti-microbial and UV resistance of hemp organs were advantageous in utilization for functional wear, such as sportswear, as well as sustainable textile applications (Novaković et al., 2020). Higher hemp content (50:50 cotton-hemp) improves crease recovery (163° in compact suiting vs. 128° for 100% cotton) due to hemp's high elastic recovery but increases pilling (rating 2 vs. 4 in 100% cotton) due to fiber length variation (16–50 mm). Antibacterial activity improves significantly (bacterial colony counts 24 vs. 204 for cotton), indicating hemp's inherent bio-resistance. (Ahirwar & Behera, 2021).[26-30] Hemp properties can also be modified by the way the fabric is woven and how the yarn is processed. Running studies for plain, twill, and Panama weaves show that the denser the fabric structure for the weave and the higher the content by weight of hemp, the more mechanical strength is gained, but at the expense of adequate drape and hand feel (Vasile et al., 2024). Using more than two fiber types (organic cotton-viscose-hemp) decreased fabric uniformity and increased imperfections. However, viscose-hemp (two-fiber) blends exhibited a synergistic effect, enhancing flexibility as viscose compensated for hemp's low flexibility and overall comfort properties. (Okyay et al., 2023). In contrast, loosely woven hemp-linen blends provide greater pliability and comfort, due to the smoother flax fibers of damn their inherent stiffness (Okur, 2022). Research conducted on different techniques of yarn twisting and blending has established that yarn folded on each other increases the softness of textiles while keeping their durability for r long makes make it suitable for apparel textiles (Stanković, 2019). Hemp fiber extraction via the retting process also affects final fabric performance as enzyme-treated hemp fibers provide a softer and more flexible textile than those that are traditionally processed (Zhang et al., 2016). So, if the blend ratios and processing techniques can be optimized, mechanical strength can be balanced with high wearer comfort, making hemp-based fabrics more versatile for textile applications.[31-33]

2.5 Yarn Tenacity

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e ISSN: 2584-2854
Volume: 03
Issue:03 March 2025
Page No: 654 - 664

An in-depth analysis of the hemp and hemp blended yarns enables an understanding of their features that contribute to the mechanical strength, durability, and comfort of the fabric. The high stiffness of fiber, abundance of cellulose, and increased staple fiber length all contribute to its excellent fabric characteristics. When blended with cotton/flax, the greater tenacity of hemp fiber gives rise to higher tensile and tear strength in the fabric (Vasile et al., 2024; Kim & Kim, 2018). The low strain energy at the break, however, makes pure hemp fabrics cruel stiff, and unfriendly. As a result, the fabrics are drape-resistant and fairly soft (Okur, 2022; Ahirwar & Behera, 2021). In hemp blended yarns, the presence of cotton, linen, or Tencel offers improved flexibility and comfort due to their greater elongation and lower stiffness, which mitigates the excess mechanical rigidity that hemp delivers (Mariz et al., 2024). The tenacity of blended yarns is dependent upon the ratio of blend and the compatibility of the fibers and a 30-50% blend of hemp is preferred, due to its high strength and improved pliability of the fabric (Shuvo, 2020). It is noted that tighter weave structures in high-tenacity hemp blended fabrics are mechanically durable, but the fabrics may become less comfortable and more rigid. The selection of fabrics for different purposes becomes an issue (Baitab & Abbas, 2024). Higher yarn tenacity in hemp blends enhances comfort by improving moisture-wicking and thermal regulation due to hemp's higher moisture regain compared to cotton. This property allows hemp fibers to absorb and release moisture efficiently, contributing to better thermophysiological balance (Atav et al., 2024). The bleaching process has significantly influenced the mechanical properties of wet-spun hemp yarn, particularly its tenacity. It improved the tenacity from 25.74 cN/tex to 34.19 cN/tex, enhancing mechanical durability due to structural modifications while retaining the fiber's high rigidity and low elongation (2.43%) (Tripa et al., 2023) In addition, hemp tossing yarns with higher tenacity have improved pilling resistance and wear durability them, thus making the cotton and hemp blends useful in long-wearing textiles such as denim (Stanković & Novaković, 2019). Chemical retting and enzymatic treating herbal blends are also found to improve fiber fineness and decrease the stiffness and roughness of the material while still having good strength properties (Zimniewska, 2022). It can be observed that while pure hemp yarns are stronger, they lack useful softness and comfortability. Therefore, softening agents make hemp blended textiles suitable for versatile sustainable fabrics. [34-40]

3. Effect of Fabric Constructional Parameters

3.1 Weave structure

Mechanical properties of hemp and hemp-interwoven fabrics are strongly affected by the weave used, and thus tensile strength, elongation, drape, and stiffness. Research indicates that plain weaves have higher tensile strength and lower flexibility owing to the close interlacing and this limited the range of motion and thus the dimensional stability (Vasile et al., 2024; Behera et al., 2022). On the other hand, twill and satin weaves, with shorter floats and narrower interlace points, are more stretchable, have better drape, and have less tensile strength, which justifies their use as a material for fashion and soft textile applications (Stanković et al., 2024). Plain weave hemp-cotton blend fabric enhances tensile strength and durability (399 N warp, 478 N weft for suiting) but increases stiffness and roughness (MIU 0.270 vs. 0.130 for cotton) due to hemp's higher bending rigidity and surface friction. (Ahirwar & Behera, 2021) The bending rigidity of hemp fabrics is directly related to the crystallinity of hemp cellulose fibers, which, in plain weave structures, results in a stiffer fabric compared to looser weaves like basket and panama, where yarn movement allows for more flexibility (Puttaswamy, 2024; Zimniewska, 2022). The inherent natural hollow shape and high stiffness of hemp fibers provide for smaller flexural deformation, and consequently, hemp-based plain-woven fabrics are less elastic (i.e., more of a rigid structure) than, for example, cotton or flax yarn fabrics, which is why hemp-based plain-woven fabrics are by nature rougher and stiffest (Zhang et al., 2016; Stanković, 2022). Mix hemp itself with softer materials, e.g., linen, flax, Tencel, and softer weave structures, e.g., twill, and crepe, can change tactile properties and increase wearer comfort (Kim & Kim, 2018; Mahmood Baitab et al., 2024). Comfort-related

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e ISSN: 2584-2854
Volume: 03
Issue:03 March 2025
Page No: 654 - 664

properties such as thermal regulation, moisture management, and breathability are highly influenced by the weave structure itself. More loosely woven fabrics (such as basket weave, crepe weave, and leno weave) provide far higher air permeability and moisture-wicking action which makes them ideal for staying comfortable in hot and humid conditions (Novaković et al., 2020; Okur 2022). In contrast, dense weaves such as plain cloth and twill trap more air and thus have good thermal insulation properties however cold air transfer therefore poor for restraining breathing making them suitable for applications where warmth is desirable (Saricam, 2022; Stanković et al, 2019). Additionally, the moisture absorbency from hemp is comparable to cotton and flax which are approximately 12% of the weavable weight this gives very good comfort especially when blended with these fibers since the fibers enhance thermal insulation and sweat-wicking properties collectively (Demir, 2020; Zimniewska, 2022). In another study on hemp which has been featured with banana fibers, it was found that when the hemp fabric and the banana fibers were blended thermal insulation properties were greatly improved with the combination of the two fibers. Furthermore, when hemp and ramie were blended with a large amount of hemp, the fabric exhibited an extra high level of breathability and moisture transport properties which made the fabric very effective at cooling off the wearer when they were sweating (Rani et al. 2019). Further studies on the production of hemp-based denim fabrics suggest that post-production treatments such as industrial washing are very important processes which in turn significantly affect the final comfort properties of the materials that have a double look at the softness and easy handling of the fabric surfaces (Saricam, 2022). Overall weave selection is given great consideration in fabric performance as well as balance between mechanical durability and comfort properties and making amendments to the fiber blend or in finishing processes can significantly enhance the performance of the hemp fabrics that are being considered for a variety of applications. [44]

3.2 Thread density

Thread density as defined by the ends per inch (EPI) and the picks per inch (PPI) have a significant influence on the mechanical and comfort properties of hemp and hemp blend fabrics. A higher thread density improves strength and wrinkle resistance but reduces air permeability and flexibility. Cotton-hemp (50:50) with compact spinning had higher stiffness (7.92) and lower fullness (4.44) compared to cotton (stiffness 6.31, fullness 5.03) due to hemp's coarse and high-density structure. (Ahirwar & Behera, 2022). The enhancement of fabric integrity is attributed to the compact weave structure, which allows for the dissipation of stress more effectively than the hemp fabric using 75 EPI 65 PPI which was substantially reduced in global tear strength, and because of this reduction, the water resistance properties are impaired. Housed within the 100% hemp fabric which has 75 EPI 65 PPI base we use 19% greater tear strength than a combination of the hemp and linen content relief 19% because of the usage of hemp curvatures muscles that provide an elastomeric resistance very superior to that obtained from cotton (Vasile et al., 2024). However, at extremely high densities where the density exceeds 80 EPI, yarn crimping increases which will reduce bending recovery and fatigue resistance of the material. This makes the fabric inflexible hence more likely to become stiff due to the reduced pore size in the inter-fiber space restricting airflow (Khan et al., 2024). Hemp fabric which has a 40 50 EPI 30 PPI total permeability reduction has a greatly inferior air permeability to a piece of 35 30 EPI 30 PPI material which while exposed to the same salient parameters allows for an equivalently low overall air permeability providing 33 reductions in air permeability (this result is indicative of high-density hemp fabric impairing breathability). However, by utilizing the natural lumen features of the hemp fabric and the high moisture regain of the fabric maximizing the range of 12% when the texture and density are suitably low the body of the garment transfers moisture dielectrically with minimal effect (Stankovic et al., 2019). In the blends which are made from the fiber of hemp and linen, an appropriate balance of comfort and mechanical properties are achieved at moderate densities of thread equivalent of 50–60 EPI 40–50 PPI which maximizes the integrity

e ISSN: 2584-2854
Volume: 03
Issue:03 March 2025
Page No: 654 - 664

of the fabric ensuring that there are acceptable levels of breathability whilst also giving rise to response to fluidity whilst also avoiding re-organization of the fiber which gives rise to a higher stiffness in the fabric (Ahirwar Behera, 2022).[42]

3.3 Areal density

The mechanical and comfort properties of hemp as well as hemp blends are greatly affected by areal density (GSM) and this is due to changes in fiber porosity, and fiber distribution leading to changes in the structural integrity of the fabric. Higher GSM fabrics which are greater than 200 g/m² are found to have tensile strength and abrasion resistance which is influenced by a denser fiber network therefore the fabric is made durable but also loses its elasticity due to the formation of a tight elastic fabric (Abbas et al., 2023). Hemp-based fabrics that have a GSM value of greater than 220 g/m² demonstrate superior tensile strength as the result of hemp having a high cellulose content (57 - 77% and its fiber was found to be stiff naturally which was further supported by that found by Abbas et al 2023. Hemp/cotton blends at 128 GSM give better strength than pure cotton which can be attributed to the higher fiber modulus of hemp and therefore the structural integrity of the fiber (Hasan et al 2022). [41] However, for situations in which the GSM is greater than 300 g/m², the lack of structure and stiffness reduces the suitability of these fabrics for use in apparel applications (Asfand & Daukantienė, 2022). Higher GSM improves the thermal resistance but simultaneously compromises breathability through increased air permeability. Hemp-based crepe fabrics are a case in point which has a GSM greater than 200 g/m² which is said to benefit from more resistance to thermal transmission; on the other hand, they suffer the effects of a diminished moisture-wicking capacity owing to the enhanced density of fibers in the fabric (Baitab et al., 2024). Conversely, fabrics with GSM values under 180 g m² have superior air permeability and moisture manageability and as a result would be more suitable for summer and activewear applications (Islam et al., 2022). Hemp-based polyesters are superior at abrasion resistance at higher GSM but suffer from reduced flexibility with the opposite trade-off between comfort and mechanical durability (Repon et al., 2024). Fiber length, blend ratio, and weave structure all have an impact on the effects displayed by the product, and at higher GSM an increase in the length of hemp fibers leads to an increase in tensile strength while decreasing the fiber length will lead to an increase in softness and drape (Yilmaz et al., 2011). Thread density thus has important effect on the performance and comfort properties, where a higher density leads to forming fabrics with higher strength and wrinkle resistant but negatively affects its breathability making a less porous weave structure and stiffer. Therefore, a balanced thread per unit length is essential in keeping both mechanical and comfort properties maintained, without compromising on flexibility and air flow.

3.4 Number of Pores

The number of pores in both hemp and hemp blend fabrics is a major determining factor in the performance of materials breathability, comfort and to an extent, for the mechanical properties too. Studies demonstrate that having larger pores enhances air permeability, moisture wicking as well as thermal regulation by allowing for greater air permeability. This leads to softer fabrics however at the cost of reduced durability (Saricam, 2022; Stankovic Bizjak, 2014). In contrast, a denser weave with fewer pores will provide better tensile strength, microbial resistance as well as UV protection (Rogina-Car et al., 2020; Kocić et al., 2019). Hemp fiber structure, with natural porosity and stiffness, influences fabric behavior—more open-pored fibers enhance thermoregulation and absorption, and more compact fiber structures improve durability (Kostic et al., 2014). Hemp fiber structure, with intrinsic porosity and stiffness, determines fabric behavior—more open pore fibers enhance thermoregulation and absorption, while denser fiber structures provide increased durability (Kostic et al., 2014). Apart from oxidative and alkaline treatments which directly modify surface pore structures, the mechanical strength of the treated materials and comfort levels are also directly affected (Sąsiadek et al., 2024). In blended and treated hemp textiles pore behavior varies depending on folded yarns, washing processes, and structural modifications. Research on hydro-entangled Cotton/Lyocell fabrics has demonstrated

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e ISSN: 2584-2854
Volume: 03
Issue:03 March 2025
Page No: 654 - 664

improved moisture management and air permeability due to pore realignment (Kim Kim, 2018). Studies have observed that knitted hemp textiles have pore size differences which lead to changes in the feel, durability, and breathability of the fabric, particularly when the tensile density of the yarn increases which also decreases the pore size (Stankovic, 2014). Likewise, when hemp denim fabrics are processed by industrial washing techniques air permeability and softness increase, and as washing also increases the pore volume (Saricam, 2022). Moreover, microbial permeability studies suggest that the weave pattern decisively alters pore effectiveness, with satin weaves reducing bacterial penetration compared to basket weaves (Rogina-Car et al., 2020). In a study of woven hemp crepe fabric, less number of pores present resulted in higher durability of the fabric but decreased its thermal comfort The role of the number of pores in the thermophysiological of textile fabrics is further highlighted in woven hemp crepe fabrics in which smaller pores increase the strength of the textiles but with a reduction in thermal comfort characteristics (Baitab , 2024). Furthermore UV, protection studies reveal that woven fabrics which have small pore sizes, limit exposure to UV light but will reduce airflow within the fabric thus making the cloth unsuitable for summers (Kocić et al., 2019). Finally, consumer evaluations suggest that hemp-based clothing with optimized porosity achieves an optimal balance between breathability, durability, and comfort, making pore distribution a critical factor in textile engineering and product development (Stanković, 2023). Therefore, it is understood that pore size and number have a good influence on the mechanical and comfort properties, with higher influence on the breathability and antibacterial efficiency. And the number of pores (the porosity) is too decided according to the end uses application intended. [43]

4. Future Scope

Future studies should explore spinning enhancement techniques to be developed for increasing hemp yarn's tenacity, flexibility, and elongation using various rotor, vortex, and compact spinning. Low-twist hemp yarn can be developed to enhance comfort for applications immediately next to the skin surface. Further optimization of blending ratios will be helpful for hemp balancing, with mildew resistance to increased moisture-wicking and elasticity, especially for the blends of hemp with Tencel, cotton, and bamboo. Modifying the weave structures at this stage could further enhance mechanical durability and thermoregulation properties, like using a loose basket and crepe weave for breathable applications. Explore thread density and GSM optimization for development in the strength and air permeability balances necessary for active and protective textiles. Further, finishing treatments will also include antimicrobial functionalization, enzymatic softening, and UV-resistant coatings for extending hemp in its applications for medical, performance, and outdoor uses. Finally, green commercial viability and sustainable dyeing and processing techniques should be developed. [46-47]

5. Summary

This review highlights the very important roles played by the yarn and the different other fabric parameters that influence the mechanical and comfort performance of hemp and hemp blends. High tenacity and elongation properties are provided by the ring-spun yarns, while rotor and air-jet spun yarns enhance the abrasion resistance and moisture-wicking performance characteristics. Thinner yarns would increase drape and elasticity, while coarser yarns would have improved breathability and thermal insulation because of their higher porosity and lignin content. Twists would increase tensile strength but would affect the moisture absorption downward. Lower twists would improve softness and air permeability, thus rendering them not so durable. Therefore, a blend of hemp with cotton, Tencel, or flax will equally improve flexibility, moisture absorption, as well as microbial resistance; hence, functional and breathable textiles would be available. However, fabric construction is of utmost importance, as a plain weave is said to have great potential in terms of mechanical strength, while twill and satin patterns give better drape and elongation. Higher thread density and gsm will also result in better durability and abrasion resistance but reduce air permeability; optimized distribution of open pores makes it possible to improve breathability and

e ISSN: 2584-2854
Volume: 03
Issue:03 March 2025
Page No: 654 - 664

moisture transport. This is a very necessary understanding for custom high-performing textiles from years and years of hemp applications.

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